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# RESPONSE OF A SONORAN RIPARIAN FOREST TO A 10-YEAR RETURN FLOOD

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ABSTRACT.—In March 1991 a 10-year return flood (368 $m^3 s^{-1}$) occurred in the Hassayampa River, a perennial stream (0.1 $m^3 s^{-1}$ base flow) within the Sonoran Desert. Depth of the floodwater ranged from 2.64 ± 0.20 m (mean ± SD) near the channel to 0.47 ± 0.31 m in the highest floodplain zone (*Prosopis* forest). Flow velocity was 1.7 ± 0.6 m $s^{-1}$ and 0.9 ± 0.4 m $s^{-1}$ in these same zones. An average of 8 cm of sediment was deposited on the floodplain, with maximum deposition (16 cm) on densely vegetated surfaces 1–2 m above the water table. Native riparian vegetation showed resistance and resilience to the flood disturbance. Plants on high floodplains (e.g., *Prosopis velutina* trees and saplings, and *Populus fremontii* and *Salix gooddingii* trees) had low mortality. *Populus fremontii* and *S. gooddingii* "pole" trees and saplings were on lower-elevation floodplains and sustained varying mortality depending on floodplain elevation and depth of flood waters. For example, *P. fremontii* pole trees on 1–2-m-high floodplains averaged 6% mortality, compared to 40% for those on low floodplains (<1 m above the water table) where standing water was >2 m. Seedlings of *Populus fremontii* and *Salix gooddingii* established abundantly after the flood along overflow channels and main channel sediment bars, contributing to age-class diversity for these episodically recruiting species. The exotic species *Tamarix pentandra* had greater mortality of pole trees (62%) and low post-flood recruitment compared to *P. fremontii* and *S. gooddingii*. Survivorship of shrub species also corresponded to floodplain elevation. *Zizyphus obtusifolia* grew on high-elevation floodplains and had no mortality. Shrub species of lower-elevation floodplains underwent mortality but revegetated after the flood via asexual reproduction. For example, stem density of the dominant shrub (*Baccharis salicifolia*) declined by half but recovered to pre-flood levels by late summer primarily via stem sprouting. Dominant herbaceous plants on stream banks and low floodplains (i.e., the rhizomatous perennial grasses *Paspalum distichum* and *Cynodon dactylon*) similarly compensated for a 50% decline in cover by vegetative spread. The post-flood herbaceous understory vegetation in high-elevation floodplain zones (i.e., *Prosopis velutina* forests) remained sparse throughout the summer and shifted in composition from nearly monotypic stands of exotic annual species to more diverse mixtures of native and exotic annual grasses and forbs.

*Key words: riparian vegetation, flood flow, disturbance,* Populus fremontii, salix gooddingii, *floodplain aggradation, Arizona.*

Flood flows have been said to be the "principal driving force responsible for the existence, productivity, and interactions of the major biota in river-floodplain systems" (Junk et al. 1989). With respect to floodplain vegetation, flood flows play an integral role in the dynamics of seed dispersal, plant establishment, and species replacement patterns, maintenance of species and patch diversity, and nutrient cycling and productivity (Bell 1974, Johnson et al. 1976, Smith 1980, Long 1982, Reichenbacher 1984, Kalliola and Puhakka 1988, Lisle 1989, Skoglund 1990, Stromberg et al. 1991). Riparian forests in arid regions are particularly dependent on floodflows because forest regeneration often depends on periodic flooding of otherwise dry floodplain [illegible] (Hughes 1990).

Decreased flooding is often a greater perturbation to riparian floodplains than is flooding (Sparks et al. 1990), as indicated by the substantial vegetational changes that occur when rivers are dammed and flooding is suppressed (Reily and Johnson 1982, Pautou et al. 1991). Dam construction may result in increased riparian acreage in sediment deltas at upstream ends of reservoirs (DeBano and Schmidt 1990), but altered flow and sedimentation patterns downstream can result in decreases in plant establishment rates and loss of riparian forests (Rood and Mahoney 1990, Howe and Knopf 1991).

The size differential between base flows and flood flows of a given recurrence interval is greater in arid regions than in humid regions

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[1] [illegible]

[2] [illegible]

(Graf 1988). Large desert floods can cause substrate erosion and plant removal in systems in which stabilizing vegetative cover has been reduced by cattle grazing, base-flow reduction, or other factors (Platts et al. 1985, Gordon-Ish-Shalom and Gutterman 1989, Stromberg and Patten 1992). This occurred in large scale in late nineteenth-century Arizona when large floods on denuded floodplains and watersheds contributed to regional erosion and downcutting of streams (Cooke and Reeves 1976). Floods also can cause local extirpation of aquatic species in areas where habitat fragmentation has reduced their ability to recolonize disturbed areas (Collins et al. 1981). In general, however, because desert stream ecosystems evolved with flooding, they are able to resist or rapidly recover after flood events (Fisher and Minckley 1978, Fisher et al. 1982, Reichenbacher 1984).

Few desert streams in the Southwest have not been modified to some degree by human activities. The opportunity arises infrequently to study large floods in relatively unimpacted systems. In February and early March 1991, rainstorms caused extensive flooding in Arizona. Three-day rainfall totals within the watershed of the Hassayampa River were 7.1 cm (Wickenburg station) to 10.1 cm (Prescott station), comprising about 25% of the annual average rainfall. This resulted in peak stream flows of 368 m$^3$s$^{-1}$ (>3000 times base flow level) at The Nature Conservancy's Hassayampa River Preserve, a relatively unmodified riparian system for which there are pre-flood baseline data (Stromberg et al. 1991). A continuing series of storms and spring snowmelt produced several smaller flood peaks through the middle of April. This event provided the opportunity to study the response of the riparian ecosystem to a 10-year return flood. Our primary objectives were to quantify (1) changes in floodplain topography resulting from sediment deposition and scour; (2) survivorship of dominant riparian trees (*Populus fremontii*, *Salix gooddingii*, *Prosopis velutina*, and the exotic *Tamarix pentandra*) and shrubs (*Baccharis salicifolia*, *Hymenoclea monogyra*, *Tessaria sericea*, and *Zizyphus obtusifolia*); (3) post-flood seedling recruitment and vegetative reproduction of trees and shrubs; and (4) changes in cover and composition of herbaceous species. Secondary objectives were to compare the effects of the 10-year return flood to those of smaller prior-year floods, including a 5-year return flood (193 m$^3$s$^{-1}$) in August 1988 and and a 2-year return flood (68 m$^3$s$^{-1}$) in July 1990.

## STUDY AREA

The Hassayampa River lies within the Gila watershed of central Arizona's Basin and Range Province and drains portions of the Bradshaw, Date Creek, and Weaver mountains. It arises at about 2350 m and flows freely and intermittently through bedrock canyons interspersed with deep alluvial basins to its confluence with the Gila River at about 240 m. South of Wickenburg in northwest Maricopa County, Arizona, a shallow bedrock layer causes perennial surface flow for about 8 km. The bedrock-confined perennial reach is supplied with alluvial and basin-fill groundwater stored in a deep basin located around Wickenburg (Jenkins 1989a, 1989b). The watershed above this point is about 1800 km$^2$, approximately one-third of which is composed of mountains vegetated by *Pinus ponderosa* forests. The remainder is rolling hills and valleys vegetated by Interior chaparral and Sonoran desertscrub species.

The study was conducted along a gaining section of the perennial river reach (base flows increase from 0 to 0.11 m$^3$s$^{-1}$) at an elevation of 600 m within The Nature Conservancy's Hassayampa River Preserve (Jenkins 1989a). The river has a gradient of 6 m km$^{-1}$. The primary channel has sandy bed sediments, a width of 1–3 m, and depth of about 0.3 m. The floodplain, which ranges from about 150 to 200 m in width, in this paper is defined geomorphologically as that surface adjacent to the channel and built of materials deposited in the present regime of the river (Graf 1988). This encompasses surfaces vegetated by *Prosopis velutina* that are up to 3 m above the water table (Fig. 1), based on evidence that substrate in such areas was flood deposited (Burkham 1972, Minckley and Clark 1984). The adjacent uplands slope down to the floodplain with varying gradients. The climate is arid, with average annual rainfall of 29 cm at the Wickenburg station.

The Hassayampa River Preserve was historically grazed and used recreationally, but both impacts were eliminated in 1987 when the area was acquired by The Nature Conservancy (Richter 1992). The system may still be recovering from these prior impacts; however, there are no streams in the area that have been ungrazed for long time periods with which the

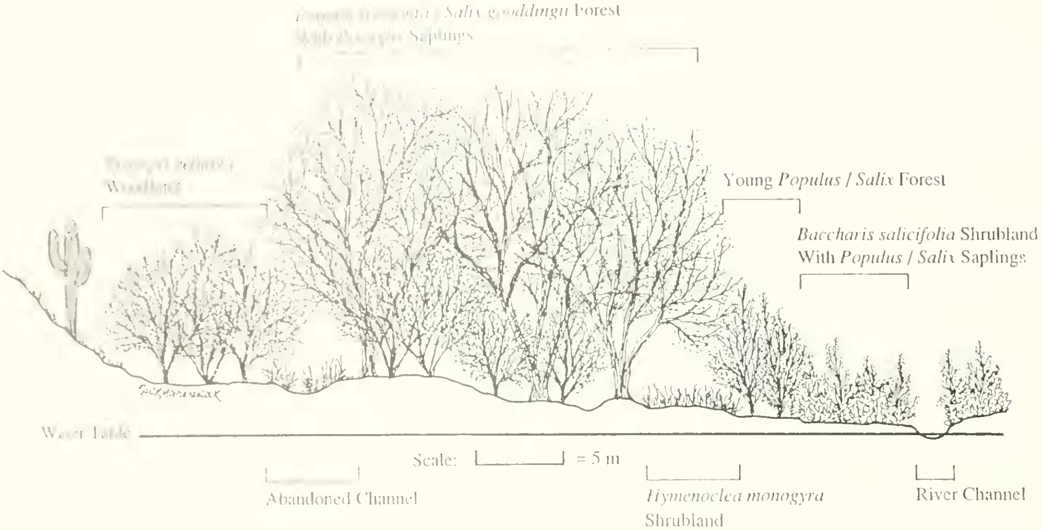

Fig. 1. Representative cross section of a portion of the Hassayampa River floodplain. Tree heights and depth to the water table are to scale.

Hassayampa River ecosystem could be compared. The herbaceous understory contains many exotic plant species, but the overstory species are predominantly native (e.g., *P. velutina*, *P. fremontii*, and *S. gooddingii*) except for a small component of *T. pentandra*. Portions of the watershed are grazed by cattle and urbanized, processes that may result in increased sediment yield or increased peak flow velocities (Von Guerard 1989, Kondolf and Keller 1991, Leopold 1991).

## Methods

Data were collected on stream discharge, floodplain aggradation and degradation, woody plant survivorship and recruitment, and herbaceous plant cover, species richness, and Shannon-Weiner species diversity. These data were obtained during the 1991 flood year and during three prior years with smaller floods. Plant nomenclature follows Lehr (1978).

### Flow Data and Floodplain Sedimentation

Daily stream flow rate (m$^3$ s$^{-1}$) during the study was measured automatically at a stream gage located ca. 0.6 km downstream of the perennial flow emergence. Depth of sediment deposited or scoured by the 1991 flood was measured by sedimentation rods (i.e., steel reinforcement bars) at 90 permanent plots (one rod per plot) throughout the floodplain. Depth was measured in August 1990 (pre-flood) and late March 1991 and May 1991 (post-flood). Fifteen of the rods could not be relocated after the flood. Relationships of sediment deposited or scoured by the 1991 flood with floodplain elevation (i.e., height above the water table), distance from the primary channel, and woody plant stem density were determined with univariate nonlinear regression analysis. Multivariate analysis was not utilized because variables were not independent (e.g., stem density and floodplain elevation). The relationship between average sedimentation within the floodplain and flow discharge was quantified with univariate regression, using data for the 1991 flood and for five smaller floods in prior years (Stromberg et al. 1991).

### Tree and Shrub Survivorship and Recruitment

Stem density of woody plants was sampled within 100 permanent, nested plots distributed throughout the floodplain. Large trees (>10 cm stem diameter at a height of 1 m) were sampled in 1989 and after the flood in 1991 in 10 × 40-m plots. Density of shrubs, tree saplings (plants <1 cm stem diameter at a height of 1 m and >1 yr old), and pole trees (1–10 cm stem diameter at a height of 1 m) was sampled in late March or early April 1988, 1989, 1990, 1991, and again in

July or August 1991 in 2 × 2-m plots. Saplings, shrubs, and trees were mapped in all years, allowing for more precise calculation of post-flood revegetation and annual survivorship in years with different flood magnitudes. Tree and shrub seedling densities were measured monthly in 1991 in 4 × 4-dm plots to document post-flood seedling recruitment.

Survivorship of shrubs, saplings, and pole trees from 1990 to 1991 was analyzed in relation to several environmental variables (stem density, floodplain elevation, and distance from the channel; and water depth, velocity, tractive shear stress, stream power, and sediment deposited during the 1991 flood) with nonlinear regression analysis. The flood flow parameters were calculated from a calibrated HEC-2 floodplain model, and floodplain elevation and distance from the channel were determined from cross-sectional surveys of the floodplain (Stromberg et al. 1991). Survivorship was analyzed for a composite data set of all shrub, sapling, and pole tree stems, and separately for three individual species (*P. fremontii*, *S. gooddingii*, and *B. salicifolia*). Survivorship was not analyzed for species with low mortality (e.g., *P. velutina* and *Z. obtusifolia*) or those in fewer than 20 study plots (e.g., *H. monogyra* and *T. sericea*).

### Herbaceous Cover

Cover of herbaceous vegetation was estimated visually within 100 permanent plots (1 × 1 m) distributed among several different overstory vegetation types. Herbaceous cover in four overstory types (*B. salicifolia* stands, *H. monogyra* stands, *Populus-Salix* forests, and *P. velutina* forests) was sampled in March and September 1988, 1989, 1990, and 1991. Cover in the streamside herbaceous type was sampled monthly during these years to document rates of post-flood recovery. To compare within-year effects of flooding, herbaceous cover by species was sampled in ten 1 × 1-m plots in flooded and unflooded *P. velutina* forests in March, April, June, and July 1991. Depth of sediment was used as the indicator of flooding. *Prosopis velutina* forests were chosen for this analysis because they occupied the highest floodplains and encompassed areas with and without flood impact. Mean cover and species richness per plot were statistically compared between flooded and unflooded forests with Student's *t* test.

Fig. 2. Daily hydrograph of the Hassayampa River during the 1990–91 water year. Data for 12–26 March were not available.

## RESULTS

### Flow Data and Floodplain Topography

The 1991 flood had peak discharge of 368 $m^3s^{-1}$ on 1 March (Fig. 2), a value about 3000 times greater than the base flow rate (0.1 $m^3s^{-1}$), about 12 times greater than the 1.5-yr bankfull discharge (30 $m^3s^{-1}$), and with a recurrence interval of slightly less than 10 years (Jenkins 1989a). Discharge remained above base flow values through mid-April. The flood inundated nearly all of the floodplain, in contrast to a 5-year return flow that did not inundate high floodplains vegetated by *P. velutina* (Table 1). Peak flow velocity in the riparian zone in March 1991, as calculated from the HEC-2 floodplain model, ranged from 1.7 ± 0.6 m $s^{-1}$ in the near-stream herbaceous vegetation type to 0.9 ± 0.4 m $s^{-1}$ in the high floodplain *P. velutina* forests. For these same areas, peak water depth was 2.6 ± 0.2 m and 0.5 ± 0.3 m (Table 1); and tractive shear stress was 12.7 ± 7.3 kg $m^{-2}$ and 3.4 ± 3.4 kg $m^{-2}$.

Surface topography was altered during the flood as a result of deposition of sediment and woody debris on floodplains, scouring of sediment from channel banks, and creation of scour pools along the main channel and in overflow channels. The 10-year return flood deposited more than twice as much sediment (8 cm) as a prior 5-year return flood (3 cm) (Fig. 3). Deposition peaked (maximum of 47 cm) on floodplain sites that were 1–2 m above the water table and declined in "bell curve" fashion on higher and lower surfaces (Fig. 4). This pattern differed from that for smaller prior-year floods in which

TABLE 1. Water depth and flow velocity on the Hassayampa River floodplain during floods of varying recurrence intervals. Values are means ± 1 standard deviation [illegible] vegetation.

| Vegetation type | Water depth (m) |  |  | Flow velocity (m s$^{-1}$) |  |  |
|---|---|---|---|---|---|---|
|  | 2-year flood | 5-year flood | 10-year flood | 2-year flood | 5-year flood | 10-year flood |
| *Baccharis salicifolia* | 1.6 ± 0.3 | 2.4 ± 0.2 | 2.6 ± 0.2 | 5.2 ± 2.0 | 6.0 ± 2.7 | 5.5 ± 1.9 |
| *Populus–Salix* saplings | 1.1 ± 0.3 | 1.9 ± 0.3 | 2.1 ± 0.3 | 3.8 ± 2.3 | 5.2 ± 3.4 | 5.4 ± 2.2 |
| [illegible] | 0.8 ± 0.4 | 1.5 ± 0.5 | 1.7 ± 0.5 | 1.9 ± 0.6 | 2.7 ± 0.7 | 3.3 ± 1.0 |
| *Populus–Salix* poles | 0.8 ± 0.4 | 1.6 ± 0.5 | 1.8 ± 0.6 | 2.2 ± 1.6 | 3.4 ± 2.4 | 3.6 ± 1.7 |
| *Hymenoclea monogyra* | 0.5 ± 0.2 | 0.7 ± 0.4 | 0.9 ± 0.4 | 2.3 ± 1.2 | 2.6 ± 0.3 | 3.2 ± 1.2 |
| *Populus–Salix* forest | 0.4 ± 0.4 | 0.8 ± 0.5 | 0.9 ± 0.6 | 2.4 ± 1.3 | 3.4 ± 1.3 | 3.5 ± 1.2 |
| *Prosopis velutina* forest | 0.0 ± 0.0 | 0.0 ± 0.0 | 0.5 ± 0.3 | 0.0 ± 0.0 | 0.0 ± 0.0 | 3.0 ± 1.4 |

Fig. 3. Sediment deposition in relation to flood magnitude of the Hassayampa River. Values represent average sediment deposition in the floodplain during the six largest floods in the period 1987–91. The regression equation is y = .0008 + .0022x (r² = .97, df = 5, P < .01).

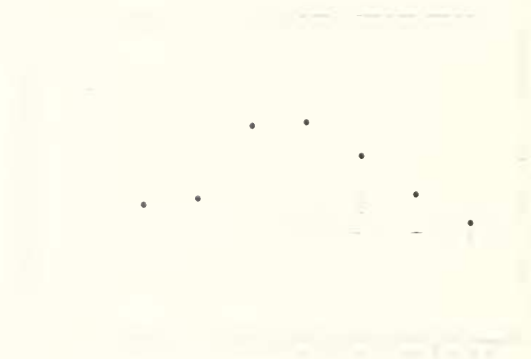

Fig. 4. Sediment deposition (means and standard deviation bars) on floodplains of various heights above the water table during a 10-year return flood in 1991 in the Hassayampa River.

sediment decreased curvilinearly with increasing floodplain elevation (Stromberg et al. 1991). Many low floodplain surfaces (<1 m high) adjacent to the main channel had a net loss of sediment in 1991, although these areas regained some sediment during small flood surges in April. The channel bed became wider and shallower in many areas but had deepened and again become entrenched in many by midsummer of 1991.

Sediment deposited during the 1991 flood was related to density of woody vegetation and to topographic position in the floodplain. Floodplain elevation and woody stem density were negatively correlated (r = −.25, P < .01, df = 84), and deposition was related to both factors (r = −.33, P = .02, df = 84, positive relationship with stem density, and r = −.47, P < .01, df = 84, [illegible] relationship with floodplain eleva-tion). Vegetation types with abundant woody stem density (e.g., *B. salicifolia* and *P. fremontii–S. gooddingii* pole stands) accumulated more sediment than did types with lower stem density (e.g., *H. monogyra* stands) (Table 2).

## Tree and Shrub Survivorship

Woody plants growing on high floodplains where flood impacts were least had highest survivorship of the 1991 flood. For the composite sample of shrubs, saplings, and pole trees, survivorship increased significantly as functions of flood water depth (Fig. 5), floodplain elevation, and distance from the primary channel (Table 4). Mature trees of *P. velutina*, *P. fremontii*, and *S. gooddingii* grew on floodplains higher than 2 m above the water table and had 100% survivorship (Table 3). Saplings of *P. velutina* grew primarily in the understory of *P. fremontii–S. gooddingii* stands and also had high survivorship

Table 2. Depth of sediment deposited or scoured on the Hassayampa River floodplain during floods of varying recurrence intervals, by vegetation type. Mean floodplain height above the water table, distance from the stream channel and density of woody stems are indicated for each vegetation type. Values are means ± standard deviation

| | Height above water table (m) | Distance from channel (m) | Woody stem density (no. m$^{-2}$) | Sediment (cm) | | |
|---|---|---|---|---|---|---|
| | | | | 2-year flood | 5-year flood | 10-year flood |
| Streamside herbaceous | 0.4 ± 0.1 | 4 ± 4 | 2.3 ± 2.7 | 9.8 ± 2.7 | 12.8 ± 4.7 | −11.2 ± 11.0 |
| *Populus-Salix* saplings | 0.7 ± 0.3 | 9 ± 8 | 9.9 ± 12.5 | 4.3 ± 4.3 | 5.4 ± 3.0 | 10.0 ± 6.2 |
| *Baccharis salicifolia* | 1.0 ± 0.5 | 22 ± 16 | 4.8 ± 4.9 | 2.7 ± 3.0 | 5.8 ± 5.7 | 13.4 ± 12.2 |
| *Populus-Salix* poles | 1.3 ± 0.5 | 22 ± 21 | 8.9 ± 4.6 | 4.2 ± 4.9 | 5.1 ± 4.2 | 14.7 ± 12.5 |
| *Hymenoclea monogyra* | 2.0 ± 0.5 | 35 ± 9 | 2.0 ± 2.1 | 0.9 ± 1.8 | 0.9 ± 1.1 | 5.8 ± 5.4 |
| *Populus-Salix* forest | 2.2 ± 0.7 | 48 ± 23 | 0.3 ± 0.8 | 0.3 ± 1.3 | 1.7 ± 2.6 | 7.8 ± 8.2 |
| *Prosopis velutina* forest | 2.7 ± 0.6 | 72 ± 20 | 0.4 ± 0.2 | 0.0 ± 0.0 | 0.6 ± 1.6 | 2.3 ± 4.2 |

(82%). Pole trees of *S. gooddingii*, *P. fremontii*, and *T. pentandra* grew on mid-height floodplains 1–2 m above the water table and had respective survivorship of 93%, 73%, and 38%. *Tamarix pentandra* was the only one of these three species that had much lower survivorship of pole trees in 1991 than in prior years. Saplings of these three species grew on floodplains <1 m above the water table, and each had about 35% survivorship of the 1991 flood.

Survivorship of the 1991 flood by poles and saplings of *P. fremontii* was significantly related to floodplain elevation, distance from the stream, and depth of floodwater (Table 4). *Salix gooddingii* survivorship showed the same trends, but relationships were not significant. *Populus fremontii* poles on floodplains 1–2 m above the water table had 94% ± 10 survival, compared to 60% ± 40 for those on floodplains <1 m high; values for saplings were 54% ± 46 for the higher floodplains and 30% ± 38 for the lower. With respect to flood water depth, *P. fremontii* and *S. gooddingii* poles and saplings showed a threshold-type response in which survivorship declined sharply where water was >1.5 m deep (Fig. 6). Sediment deposition, shear stress, stream power, and velocity were not significantly related to survivorship for either species. Between years, annual survivorship for *P. fremontii* and *S. gooddingii* saplings decreased significantly as annual maximum flood magnitude increased, with, for example, 30% of *P. fremontii* saplings surviving the 1991 flood, 43% surviving the 5-year return flood in 1988, and 58% surviving during the 1-year return flood year in 1989 (Fig. 7). In all years, *S. gooddingii* saplings had greater survivorship than *P. fremontii* saplings.

Fig. 5. Survivorship of riparian shrubs, saplings, and small trees (poles) in the Hassayampa River floodplain, 1990–91, in relation to flood water depth classes.

Survivorship by shrub species in 1991 corresponded to topographic position in the floodplain. Stem survivorship averaged 100% for *Zizyphus obtusifolia*, a species that grew on high floodplains (3.2 ± 0.6 m above the water table) vegetated by *Prosopis velutina* forests; >80% for *H. monogyra*, a species that grew on floodplains averaging about 2 m above the water table; and <20% for *T. sericea*, a low-floodplain species (1.3 ± 0.2 m) that sustained much stem breakage. Stem survivorship averaged 50% for *B. salicifolia*, the most abundant shrub in the floodplain. This species formed dense stands primarily on low floodplains (ca. 1 m high) but also grew in lesser densities on higher floodplains. Stem survivorship of *B. salicifolia* was not significantly correlated with any flood parameter.

[illegible] riparian trees and shrubs in the Hassayampa River floodplain. Data are for [illegible] (1988–89), [illegible] flood (1989–90), and 10-year return flood (1990–91).

| Species | Size class or growth form | Survivorship (%) 1988–89 | 1989–90 | 1990–91 |
|---|---|---|---|---|
| *Prosopis velutina* | mature tree[a] | NS[b] | NS | 100 |
| *Salix gooddingii* | mature tree | NS | NS | 100 |
| *Populus fremontii* | mature tree | NS | NS | 100 |
| *Prosopis velutina* | pole tree | 100 | 91 | 100 |
| *Salix gooddingii* | pole tree | 87 | 80 | 93 |
| *Populus fremontii* | pole tree | 86 | 89 | 73 |
| *Tamarix pentandra* | pole tree | 95 | 87 | 38 |
| *Prosopis velutina* | sapling | 76 | 87 | 82 |
| *Salix gooddingii* | sapling | 64 | 78 | 36 |
| *Populus fremontii* | sapling | 43 | 58 | 30 |
| *Tamarix pentandra* | sapling | 84 | 75 | 37 |
| *Zizyphus obtusifolia* | shrub | 100 | 100 | 100 |
| *Hymenoclea monogyra* | shrub | 96 | 100 | 83 |
| *Baccharis salicifolia* | shrub | 100 | 100 | 51 |
| *Tessaria sericea* | shrub | 100 | 100 | 17 |

[a][illegible] saplings are stems >1 cm diameter and are greater than 1 year in age.
[b]NS = not sampled.

TABLE 4. Regression coefficients ($r^2$ values) relating three physical parameters to survivorship of a 10-year return flood in the Hassayampa River by saplings and pole trees of *Populus fremontii* and *Salix gooddingii*; and by a composite group of riparian shrubs, saplings, and pole trees.

| | Distance from channel | Height above streambed | Water depth during flood |
|---|---|---|---|
| *P. fremontii* survivorship | 0.20 | 0.25[c] | 0.45 |
| *S. gooddingii* survivorship | 0.02 | 0.10 | 0.10 |
| Composite riparian survivorship | 0.11 | 0.13 | 0.13[c] |

[illegible]

## Tree and Shrub Revegetation

In 1991 the germination period of *P. fremontii* (March–April) coincided with the period of peak floodplain inundation. As a result, *P. fremontii* seedlings had high density and broad distribution throughout the floodplain. In April, *P. fremontii* seedlings were on floodplains up to 1.5 m above the water table (Fig. 8) and 99 m from the main channel, as well as along streambanks and overflow channels. Seedling density declined steadily through the growing season of 1991 (Table 5) due primarily to dessication. By the end of summer there were 5 seedlings m$^{-2}$ on floodplains <1 m above the water table (Table 5), a value sufficiently high to eventually produce a mature forest with characteristic density of 0.3 stems m$^{-2}$ (Table 2). *Salix gooddingii* seedlings also germinated abundantly in 1991 after the flood pulse. In May 1991 there were 618 *S. gooddingii* seedlings m$^{-2}$ in plots <1 m above the water table (Table 5). Seedlings by the end of summer were most abundant on floodplains 0.4–0.6 m above the water table. *Tamarix pentandra* germinated in June–September, after *P. fremontii* (March–April) and *S. gooddingii* (April–May). *Tamarix pentandra* had maximum seedling density of 5 ± 13 m$^{-2}$ in June 1991, but none were alive by the end of summer.

*Baccharis salicifolia* stems recovered to pre-flood densities (4.8 ± 4.5 m$^{-2}$, measured within *B. salicifolia* vegetation zones) by July 1991, primarily a result of stem sprouting and in part a result of seedling recruitment. Stem density of *Hymenoclea monogyra* increased by late summer 1991 to a value somewhat higher than pre-flood levels (2.3 ± 2.5 stems m$^{-2}$) as a result of vegetative reproduction. *Tessaria sericea* also had post-flood vegetative spread, but stem densities had not attained pre-flood levels by late summer.

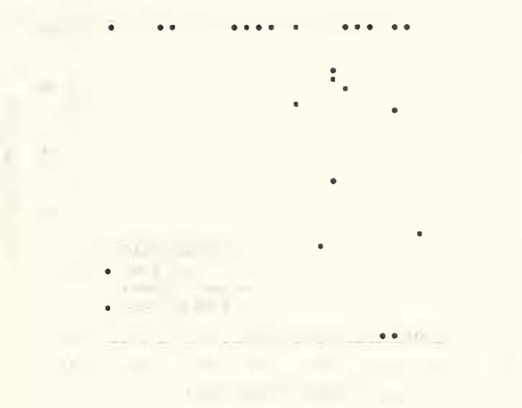

Fig. 6. Survivorship of saplings and small trees (poles) of *Populus fremontii* and *Salix gooddingii*, 1990–91, in relation to maximum water depth during a 10-year return flood.

Fig. 7. Annual survivorship of saplings of *Populus fremontii* and *Salix gooddingii* along the Hassayampa River floodplain in relation to maximum annual flood flow rate. Regression equations are: $y = 59 - 0.08x$, $r^2 = .99$, df = 2, $P < .01$ (*P. fremontii*); and $y = 82 - 0.12x$, $r^2 = .97$, df = 2, $P < .05$ (*S. gooddingii*).

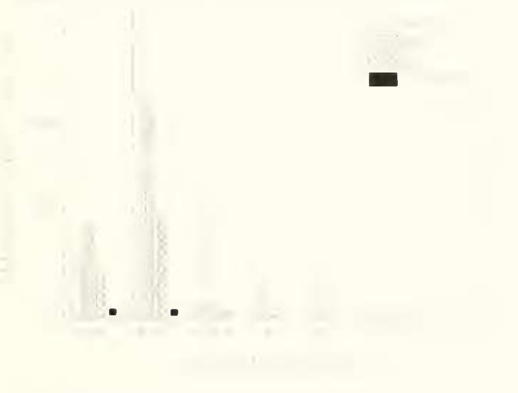

Fig. 8. Density of *Populus fremontii* in relation to water table depth, by month during 1991.

## Herbaceous Cover

Spring herbaceous cover in all vegetation types except that of the highest floodplains (*P. velutina* forests) was less abundant in 1991 than in prior years (Table 6). Herbaceous cover under *P. fremontii–S. gooddingii* forests, for example, averaged 8% in 1991 compared to 25–43% in prior years. Herbaceous cover on streambanks and in *B. salicifolia* stands was 16% and 11% respectively in late March 1991 compared to 38% and 34% in the prior year. Cover in these two areas was composed primarily of rhizomatous grasses (the native *Paspalum distichum* and the exotic *Cynodon dactylon*) and also contained lesser amounts of other natives (e.g., *Typha domingensis* and species of *Juncus*) and exotics (e.g., *Melilotus albus* and *Polypogon monspeliensis*). Cover in these areas increased nearly to pre-flood levels by September. Cover within higher-elevation vegetation types (e.g., *Populus-Salix* forests) remained low as of late summer. Within *P. velutina* forests, areas that were flooded had lower cover but greater richness and diversity of species throughout the summer compared to areas that were not flooded (Table 7). Unflooded and flooded areas in the *P. velutina* forest were both initially dominated by two exotic winter-germinating annuals, *Hordeum leporinum* and *Sisymbrium irio*. These two species continued to dominate unflooded areas throughout spring and early summer. Flooded areas, in contrast, had about 1/6th the cover of unflooded areas, and about 4–5 times as many species (e.g., 9.2 ± 1.9 $m^{-2}$ vs. 1.9 ± 0.5 $m^{-2}$, April data). These included several native annual forbs (e.g., *Amaranthus palmeri*, *Bowlesia incana*, *Amsinckia intermedia*, *Gilia sinuata*, *Lotus humistratus*, *Microseris linearifolia*, *Xanthium strumarium*, and *Verbesina encelioides*) and several exotic annual forbs and grasses (e.g., *Bromus rubens*, *Herniaria cinerea*, *Solanum rostratum*, and *Tribulus terrestris*).

## DISCUSSION

Riparian systems are noted for their resiliency, i.e., the ability to quickly return to pre-disturbance conditions. Rapid growth rates, high fecundity, and capacity for asexual reproduction are among the factors that allow rapid recovery

TABLE 5. Average seedling density (no. m⁻²) during the period of maximum abundance and at the end of the growing season for three riparian tree species on Hassayampa River floodplain surfaces < 1 m above the water table.

| | *Populus fremontii* | | *Salix gooddingii* | | *Tamarix pentandra* | |
|---|---|---|---|---|---|---|
| | April | October | May | October | June | October |
| 1988 | 111 | 0 | 385 | 0 | 11 | 0 |
| 1989 | 12 | 0 | 2 | 0 | < 1 | 0 |
| 1990 | 0 | 0 | < 1 | 0 | 0 | 0 |
| 1991 | 205 | 5 | 618 | 3 | 5 | 0 |

TABLE 6. Herbaceous cover (%) along the Hassayampa River floodplain, by vegetation type, from 1988 to 1991. Values are means ± standard deviation.

| | | 1988 | 1989 | 1990 | 1991 |
|---|---|---|---|---|---|
| Streamside herbaceous | March | 20 ± 24 | 29 ± 36 | 38 ± 31 | 16 ± 31[a] |
| | April | 38 ± 26 | 66 ± 28 | 68 ± 30 | 29 ± 37 |
| | May | 38 ± 25[a] | 68 ± 28 | 72 ± 29 | 35 ± 41 |
| | July | 66 ± 22 | 74 ± 30 | 43 ± 30[a] | 41 ± 38 |
| | Sept. | 69 ± 34 | 77 ± 30 | 60 ± 25 | 60 ± 35 |
| *Baccharis salicifolia* shrubland | March | 22 ± 18 | 19 ± 19 | 34 ± 26 | 11 ± 24[a] |
| | Sept. | 38 ± 36 | 41 ± 35 | 25 ± 21 | 41 ± 43 |
| *Hymenoclea monogyra* shrubland | March | 19 ± 16 | 20 ± 24 | 24 ± 21 | 4 ± 4[a] |
| | Sept. | 7 ± 11 | 15 ± 13 | 12 ± 11 | 13 ± 13 |
| *Populus-Salix* forest | March | 43 ± 27 | 25 ± 21 | 34 ± 31 | 8 ± 12[a] |
| | Sept. | 19 ± 29 | 21 ± 28 | 21 ± 23 | 5 ± 6 |
| *Prosopis velutina* forest | March | 84 ± 17 | 35 ± 21 | 58 ± 26 | 52 ± 45[a] |
| | Sept. | 7 ± 12 | 12 ± 16 | 10 ± 17 | 6 ± 13 |

[a] Post-flood sampling date.

TABLE 7. Cover, richness, and Shannon-Wiener diversity of herbaceous understory species in *Prosopis velutina* forests that were and were not inundated during a 10-year return flood in March 1991. Values for cover and richness are means ± standard deviations.

| | Cover (%) | | Species richness | | Species diversity | |
|---|---|---|---|---|---|---|
| Month | Flood | No flood | Flood | No flood | Flood | No flood |
| March | 7 ± 7 | 71 ± 30 | 2.3 ± 0.5 | 1.9 ± 0.6 | 0.53 | 0.91 |
| April | 18 ± 4 | 79 ± 36[a] | 9.2 ± 1.9 | 1.9 ± 0.5[a] | 2.46 | 0.73 |
| June | 12 ± 6 | 81 ± 21[a] | 10.1 ± 3.1 | 2.2 ± 0.8[a] | 2.53 | 0.45 |
| July | 16 ± 9 | 88 ± 11 | 7.9 ± 3.0 | 2.6 ± 2.3[a] | 2.31 | 1.23 |

[a] Significant difference (P < .05).

of riparian plants after disturbance (Stromberg and Patten 1989, Gecy and Wilson 1990). Densely vegetated floodplain ecosystems also can be resistant to floods, in the sense that floods may cover them without scouring vegetation or substrate (Hendrickson and Minckley 1984).

The 10-year return flood in the Hassayampa River inundated most of the floodplain and deposited a net average of 8 cm of sediment (maximum of 0.5 m). Low-elevation floodplain surfaces had greatest flow velocities (to 7 m s$^{-1}$) and water depths (to 2.8 m). The native riparian vegetation showed a mixture of resistance and resilience to this flood disturbance. Species on high floodplains (e.g., *P. velutina* and *Z. obtusifolia*) had no mortality, while those on lower-elevation floodplains variously had mortality followed by seedling recruitment (*P. fremontii* and *S. gooddingii*) or by vegetative reproduction (e.g., *Baccharis salicifolia*).

*Prosopis velutina* was the dominant tree on high floodplains (ca. 3 m above the water table) and had high survivorship of trees and saplings. It did not show post-flood seedling recruitment, consistent with prior studies indicating that *P. velutina* seeds germinate primarily after late summer floods (Stromberg et al. 1991). *Populus fremontii* and *S. gooddingii* trees grew on floodplains 2–3 m high and also had high survivorship. Young trees and saplings of these two species were on younger, less aggraded floodplains and sustained some mortality. *Salix gooddingii* saplings and poles had lower mortality than did *Populus fremontii*, perhaps because of greater stem pliability and tolerance to saturation (McBride and Strahan 1984, Hunter et al. 1987). Survivorship of both species was greater on sites where flood waters were shallowest, a factor reported to be an important determinant of flood survivorship in other riparian systems (Stevens and Waring 1988). The relationship between water depth and survivorship may be an expression of effects of flood hydraulic force on plant removal or mortality via abrasion and stem breakage, rather than of a causal relationship between root saturation and mortality. Although correlations of mortality with flood velocity and shear stress were not statistically significant, this may have been due to chaotic movement of water and sediments on the floodplain, which are not adequately represented by flood-simulation models such as HEC-2.

The 1991 flood created optimal seedling recruitment conditions for *Populus fremontii* and *Salix gooddingii* by scouring channel banks and depositing new sediment on stream banks, reducing herbaceous and overstory competition (at least temporarily), and moistening floodplains at an appropriate time (during seed dispersal) and place (moderately high surfaces above the zone of frequent summer flood scour) (Stromberg et al. 1991). Tree-ring studies have shown that *P. fremontii* and *S. gooddingii* establish in large scale about once a decade within the Hassayampa River system, during or after years with large flows ($>250$ m$^3$s$^{-1}$; 7-year return flood) (Stromberg et al. 1991). This present study confirms the role of large floods in increasing age-class diversity for these episodically recruiting species.

The exotic *T. pentandra* co-occurred with *Populus* and *Salix* but had greater mortality of pole trees than did the native trees. Mortality of *T. pentandra* more likely resulted from intolerance to physical flood effects than from physiological intolerance to inundation (Warren and Turner 1975, Irvine and West 1979). *Tamarix pentandra* had low post-flood seedling establishment, due in part to a low density of mature seed-producing trees in the Hassayampa floodplain and in part to the fact that the flood occurred several months prior to *T. pentandra* seed germination and thus did not moisten potential germination sites at an appropriate time (June through October). Additionally, much of the available "germination space" during its germination period was preempted by herbaceous cover and by seedlings of *P. fremontii* and *S. gooddingii*, species that precede *Tamarix pentandra* in the chronosequence of tree species germination at the Hassayampa River.

Vegetative reproduction is a common post-disturbance revegetation mechanism in floodplain systems (Gecy and Wilson 1990) and was demonstrated by all shrub species in the Hassayampa River floodplain that had flood mortality. Extent of flood mortality of shrub species at the Hassayampa varied with their topographic position in the floodplain. *Zizyphus obtusifolia*, a species of high floodplains (ca. 3 m above the water table), had no mortality. *Baccharis salicifolia* underwent a 50% decline in stem density during the flood but increased to pre-flood densities by late summer primarily via stem sprouting. *Hymenoclea monogyra* and *T. sericea* are both clonal shrubs that spread via root sprouts after mechanical injury (Gary 1963) and via shoot sprouts after stem burial. *Hymenoclea monogyra* compensated for flood mortality by vegetative reproduction; but this was not the case for *Tessaria sericea*, a low-floodplain species that had high flood mortality. Other studies also have reported low flood survivorship for *Tessaria sericea* (Stevens and Waring 1988).

Vegetative reproduction also was the dominant revegetation method for herbaceous plants along stream banks and low-elevation floodplains. Cover in these areas declined by about half after the flood but recovered to pre-flood levels by late summer. Flood-tolerant perennial rhizomatous grasses ([illegible] and *C. dactylon*) dominated these areas during and prior to the flood but species less tolerant of high flow velocities (e.g., *Typha domingensis*) may ultimately increase in abundance during flood-interim periods (Fisher et al. 1982, Hendrickson and Minckley 1984). Understories of high-elevation floodplains showed changes in cover and composition after the 1991 flood. Prior to the flood *P. velutina* forests were dominated by dense, nearly monotypic stands of exotic annual species (e.g., *Hordeum murinum*) that probably had become established during past years of cattle grazing and other exogenous disturbances (Wolden et al. 1991). After the flood these areas had lower cover but greater richness of herbaceous species and greater relative abundance of native annuals. We speculate that compositional changes were due to reduced competition with entrenched exotics, an influx of flood-borne seeds from upstream areas or other vegetation types within the floodplain, or altered edaphic conditions resulting from deposition of sediment with different texture or nutrient content (Stevens and Waring 1988).

Fluvial processes including floodplain aggradation and formation of microrelief patterns (e.g., backwater depressions) contribute to the diversity and "mosaicism" of riparian plant communities in many flood-driven ecosystems (Kalliola and Puhakka 1988). Within the Hassayampa floodplain, as well, variable sediment deposition and scour patterns contributed to "patchiness" within the riparian floodplain. For example, localized light gaps were formed in areas with major debris deposition, and scour pools (i.e., backwater depressions) were formed along main channels and in overflow channels. Floodplain sedimentation accentuated the existence of hydrological gradients (e.g., gradients of depth to groundwater), which contribute to floristic diversity within riparian ecosystems of the Hassayampa River and elsewhere (Hupp and Osterkamp 1985, Bravard et al. 1986, Stromberg et al. 1993).

The 10-year return flood resulted in greater floodplain aggradation and greater woody plant mortality than smaller prior-year floods. Effects of floods larger than the 10-year event can only be speculated upon. A 100-year return flood in 1970 in the Hassayampa River (Jenkins 1989a) apparently did not cause extensive loss of riparian vegetation, as evidenced by the presence of extensive stands of *Populus* and *Salix* trees that established in 1959, 1952, and earlier (Stromberg et al. 1991). The 10-year return flood probably reached a "geomorphic threshold," that being the level at which substantial change in floodplain morphology and vegetation begins to occur, based on studies of other desert rivers that implicate the 5-year return flow as a threshold discharge for channel and floodplain instability (Graf 1983).

Other potential effects of the flood on riparian vegetation such as changes in plant productivity as a result of nutrient or water pulses were not addressed in this study, nor was the role of vegetation in moderating flood processes explicitly addressed.

Data in this paper suggest that floodplain vegetation aided in stream bank stabilization and sediment trapping, important functions of wetland and riparian vegetation (Fisher and Minckley 1978, Cooper et al. 1987, Sullivan and Stromberg 1992). The vegetation also may have enhanced groundwater recharge and reduced the downstream impact of flood flows by reducing flow velocities and increasing water retention time within the floodplain (Burkham 1976, Beschta and Platts 1986).

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